

## **Linked VORTEX Model for Mine Burial Prediction**

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### **LONG-TERM GOALS**

The long-term goal is to perfect our process-based model for the prediction of scour and burial of mines deployed in the shallow waters of the global coastal zone; and to use this model to develop principles of scour/burial mechanics with general application to the nearshore, as well as perfect mine burial procedures that can be used by the fleet. We are presently pursuing these goals by expanding the physics and validation of the model to treat mine burial as a global problem using a hierarchy of interactive inputs for both mine type and coastal type.

### **OBJECTIVES**

The basic scientific objective is to determine the appropriate geomorphic and hydrodynamic principles and evaluate their application to:

- mine migration (walking)
- locally rapid mine burial
- time varying burial/exposure throughout the littoral cell
- identification of mine migration and burial tendencies according to mine properties (size, shape, weight) and coastal type
- scour/burial application to other objects and structures in the coastal zone

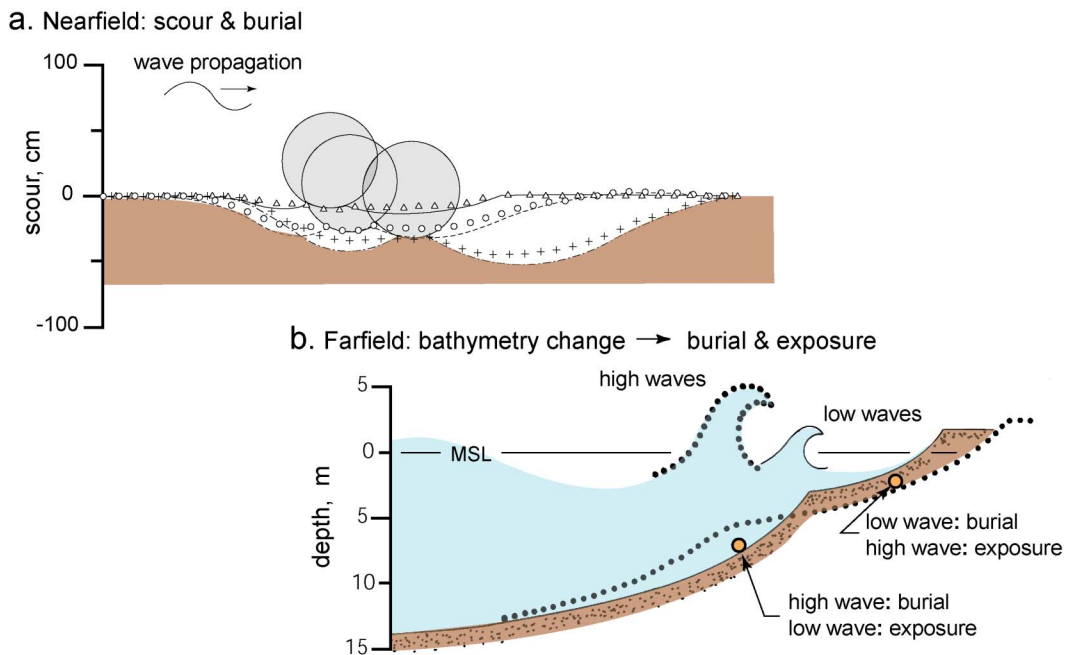
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These objectives are being accomplished by upgrading model physics, expanding validation efforts using both archival and contemporary data sets, and performing sensitivity analyses to identify general mine burial principles (rules of thumb). When possible we apply these principles and related codes to benefit other Navy programs. These efforts have resulted in the development of a Mine Burial Primer for Fleet Use (Inman and Jenkins, 2002), a user manual for operating the model (Jenkins and Inman, 2004) and an invited presentation on mine burial prediction at the ONR Joint Review of Technology Applicable to Mine Countermeasures, Naval Surface Warfare Center, Panama City, FL, 17-20 Feb. 04. We are preparing a paper for publication “Scour and Burial Mechanics of Bottom Mines and Other Objects in the Nearshore,” for the *Journal of Oceanic Engineering*.

## APPROACH

We have developed a process-based model for mine migration, scour and burial prediction. VORTEX consists of two coupled sets of mechanics, each with distinct scale regimes (Figure 1). *Nearfield* burial mechanics involve length scales on the order of the size of the mine and its immediate surroundings (~10 m), while *farfield* burial mechanics involve length scales of the order of the littoral cell (~50 km) (Inman and Jenkins, 1996, 2002; Jenkins and Inman, in review). The nearfield burial is computed with vortex lattice computational techniques that predict the vortex field around the mine and drive Bagnold sediment transport mechanics to ultimately predict burial by scour (Figure 2). Sediment budget formulations and thermodynamic formulations of the equilibrium bottom profile are used to predict burial by large-scale bottom elevation changes occurring over the farfield.

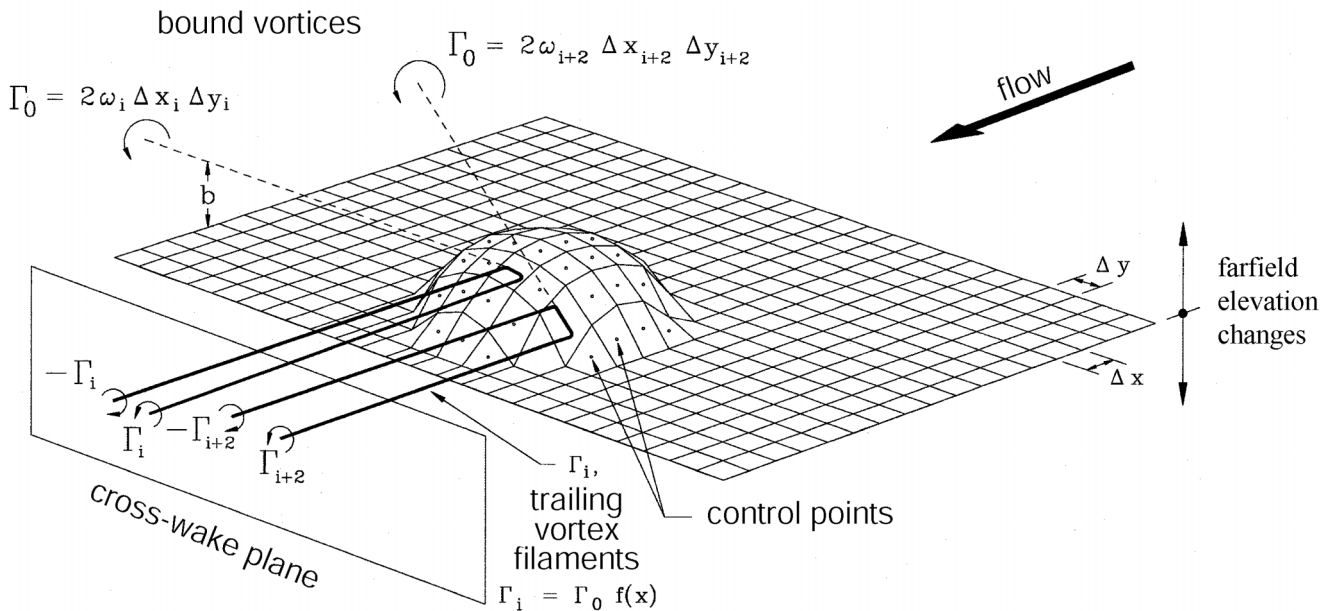
We have improved VORTEX by developing code for movable boundary conditions within the existing architecture. Movable boundary conditions in the nearfield account for mine migration by burial



**Figure 1. Mechanics of burial and exposure of seafloor objects. (a) Nearfield scour and burial, and (b) Farfield bathymetry changes due to seasonal profile changes and/or net decrease/increase in source material (after Inman and Jenkins, 2002).**

sequences involving scour and roll, scour and slip, and sometimes saltation trajectories of the mine itself (Inman and Jenkins, 2002). Movable boundary conditions in the farfield involve seasonal equilibrium profile change and accretion/erosion waves from sediment flux associated with rivers and other sources. The code for the farfield boundary conditions is based on advection/diffusion solutions for the mass balance within a set of control cells whose boundaries define the computational domain of the farfield, usually extended to cover the entire littoral cell as a single geomorphic compartment. Series of control cells are coupled in the alongshore direction, with dimensions of sufficiently fine scale to resolve coastline curvature and heterogeneity of sediment properties. Within each control cell the equilibrium and/or disequilibrium bottom profiles are specified from thermodynamic principles after Jenkins and Inman (in review).

The challenge of making predictions in diverse coastal environments has been addressed by reducing model initialization to a manageable number by means of a geomorphic coastal classification system (Inman and Nordstrom, 1971; Inman, 2004). The classification module in VORTEX selects the relative scaling for the littoral cell and associated control cells and assigns the sediment sources and sinks to which a particular burial site belongs. The classification includes three general tectonic types of coasts with their morphologic equivalents, and two types associated with latitudinal extremes: 1) collision coasts with narrow shelves and steep coastal topography resulting from collisions between two or more tectonic plates; 2) trailing-edge coasts that are on the stable, passive margins of continents with broad shelves and low inland relief; 3) marginal sea coasts that are semi-enclosed by island arcs and thereby fetch limited; 4) cryogenic coasts that are affected by ice processes; and, 5) biogenic coasts that are formed by fringing coral reefs or mangroves, etc. The coastal classification system provides a pyramid of interactive inputs that gives rapid assessment of error propagation and sensitivity of prediction to leading order inputs (Inman, 2004).



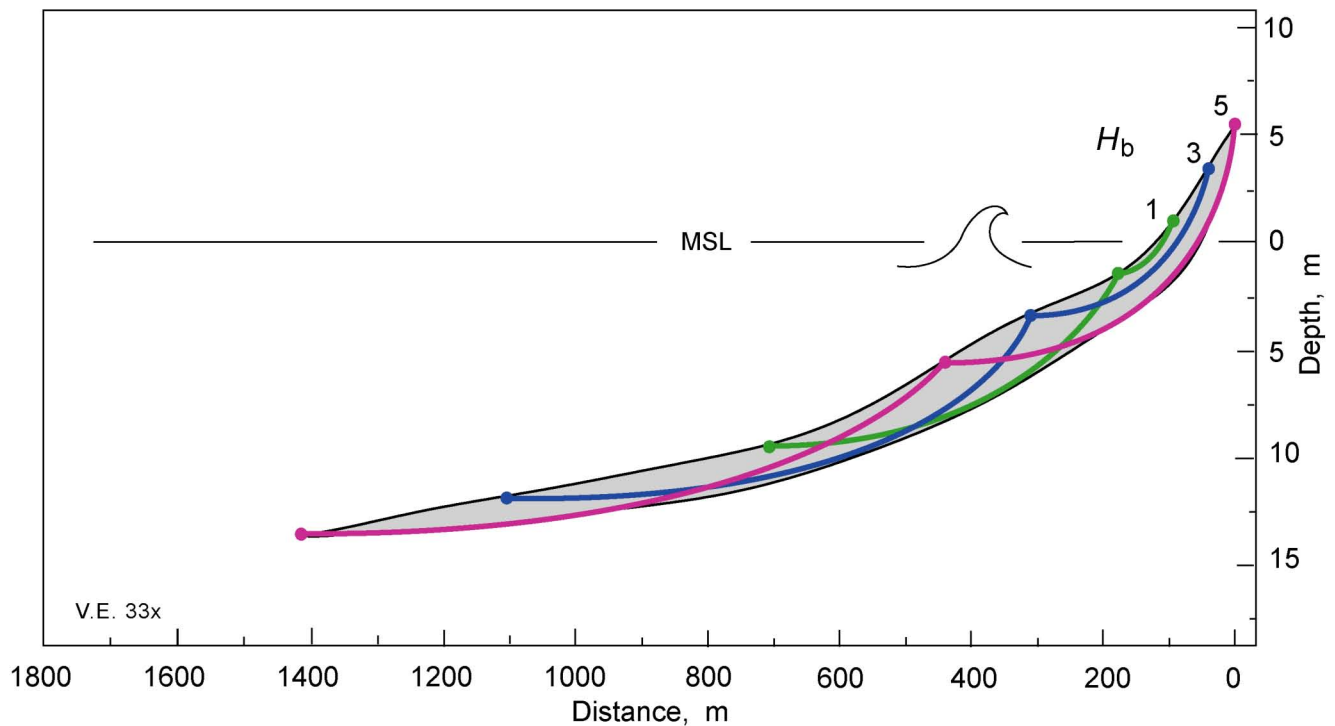
**Figure 2. Vortex lattice method for predicting the vortex field of a body of arbitrary shape resting on the seabed (from Inman and Jenkins, 2002).**

## WORK COMPLETED

VORTEX has undergone new coding for validation and upgrading, providing more efficient equation solvers and more sophisticated movable boundary conditions. New nearfield code has been developed to deal with small radius or faceted features on mines (e.g. ROCKAN mines) or small diameter mines (e.g., conventional bombs and naval projectiles re-fitted with mine firing devices). Small radius mine features require fine mesh grids that usually require large computational files and long run times that present computational stability and data storage concerns. To deal with these issues, the bound vortex of each panel in the vortex lattice was reduced by an analytic simplification to a single point vortex multi-pole centered at a control point (Figure 2). This arrangement is numerically a more efficient representation of the mine's aggregate vortex field than that obtained by the Cartesian vortex filament formulation, but gives comparable results.

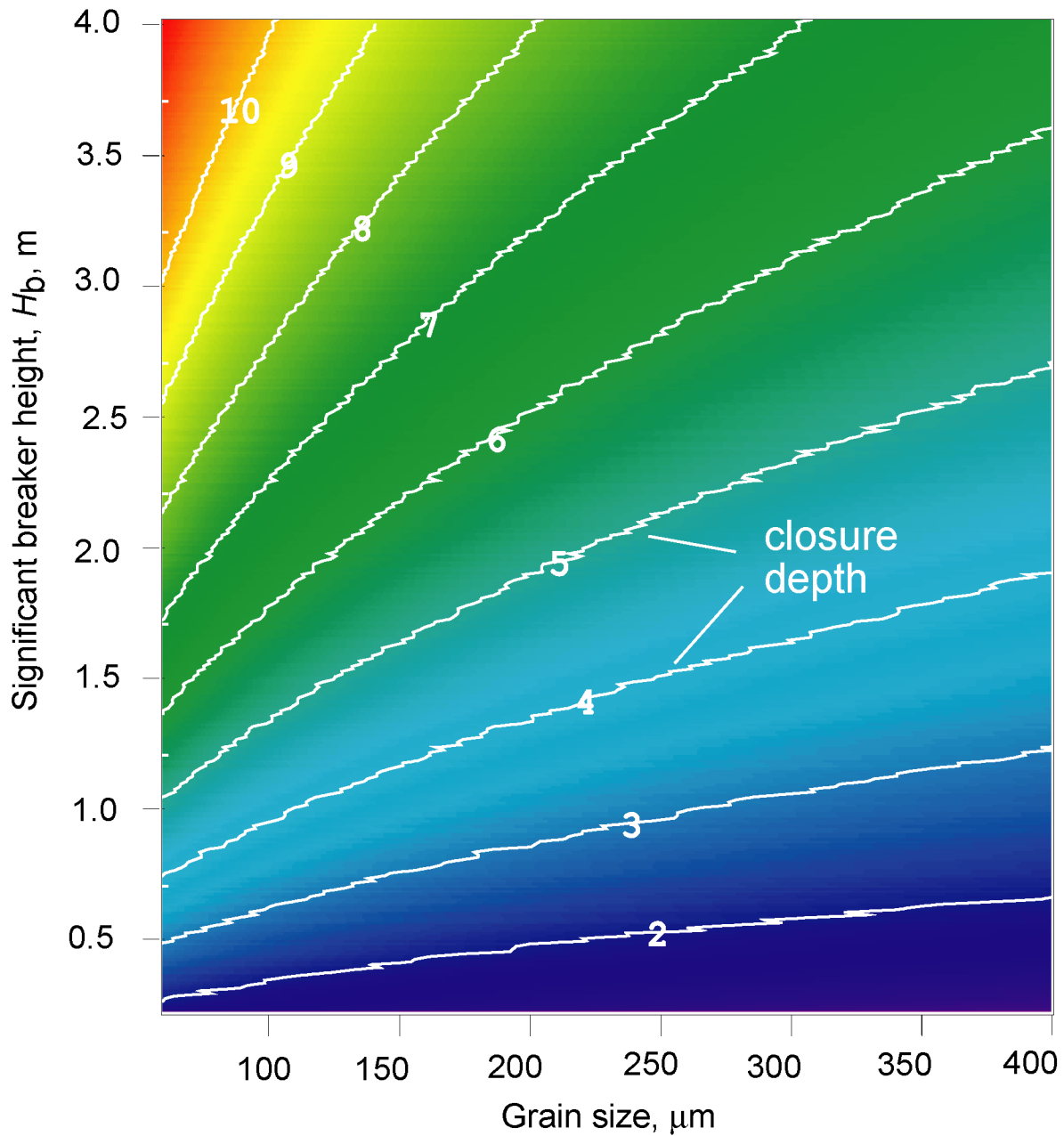
The farfield code has been made more efficient by the discovery and implementation of an exact analytic solution for the equilibrium bottom profile. In the farfield, a unique equilibrium bottom profile exists for each wave climate state, such that the bottom adjusts to maximize the dissipation of the incident waves (following the second law of thermodynamics, Jenkins and Inman, in review). These adjustments can either bury or expose a mine depending on its relative position in the cross-shore (Figure 1b) and control the rate of scour burial by changing the numbers of exposed lattice panels through the elevation of the bottom plane (Figure 2, right). By accounting for the characteristic wave climate variation of a particular site, a family of corresponding equilibrium profiles can be found that define the envelope of possible change of the farfield seabed, referred to as the *critical mass envelope* (Figure 3). The critical mass envelope is now calculated directly from an exact elliptic cycloid solution for a given family of equilibrium beach profiles (3 profiles shown in Figure 3). The cycloid solution eliminates model run-time formerly spent on numerically integrating the transcendental form of the equilibrium profile equations. Cycloid solutions of the critical mass envelope are rigorously based on empirical data in the form of extensive beach profile data taken during prolonged periods of steady wave conditions (Inman et al., 1993).

Mines residing within the envelope of critical mass (gray shaded area in Figure 2) are subject to seasonal exposure and burial in accordance with wave climate variation. Mines that impact or scour below the critical mass envelope are permanently buried, while those planted seaward of the critical mass envelope, i.e., seaward of the closure depth, are subject only to gradual or partial burial by scour (Figure 1b). Moreover, the cycloid solution is easily integrated to give the critical mass of sand required to sustain an equilibrium beach. The seaward end of the critical mass envelope is the closure depth and is a feature of great significance to the mine burial prediction problem because it delineates a depth contour beyond which burial by farfield wave-driven processes is negligible. Figure 4 gives a model-generated nomogram showing that closure depth is a simultaneous function of both wave height and sediment grain size. Such nomograms would provide fleet users a depth-based rule of thumb for partitioning mine search areas into regions of greater and lesser burial probability. When mines are planted deeper than these depths, scour burial is the only active process. Scour burial is a process which by itself does not induce total burial because burial rates slow rapidly as the degree of burial increases beyond 50% (Inman and Jenkins, 2002).



**Figure 3. Critical mass envelope (gray shading) from elliptic cycloid solution for 5 m waves with 12 s period breaking on 225  $\mu\text{m}$  sand bottom and shoaling over 125  $\mu\text{m}$  sand. Equilibrium profiles (colored) are for continuous waves with significant breaker height  $H_b$ .**

At present, the model has been subjected to field testing during FY2002-03 at three of the 5 geomorphic coastal types: 1) a collision coast off Scripps Pier, La Jolla, CA and off the Naval Amphibious Base, San Diego at Silver Strand Beach, CA; 2) a marginal sea coast off Indian Rocks Beach FLA; and 3) a trailing edge coast at Martha's Vineyard, MA. The Scripps Pier experiments involved the MANTA mine and the MK VII VSW Marker, Type AFD. There have been two series of Silver Strand Beach experiments, one involving migration and burial of PDM 1 and three mines conducted jointly with the Naval Surface Warfare Center, Panama City, FLA and the other associated with MK VII marine mammal exercises conducted by SPAWAR, Code D352. The Indian Rocks Beach and Martha's Vineyard experiments were multi-institutional efforts of the Mine Burial Prediction (MBP) Program sponsored by the Office of Naval Research. The MBP experiments measured burial of MANTA and AIM-2 acoustic mines. The burial measurements were compared with predicted burial from the VORTEX model using the DIOPS forecasting system as model input, as described below. In addition, a Mine Burial Primer (Inman and Jenkins, 2002) has been converted to electronic format and placed in the University of California Digital Library (<http://respositories.cdlib.org/sio/reference/02-8>). The Primer provides basic understanding of mine burial mechanics and rules of thumb for burial and its variability among coastal type. A detailed user manual for VORTEX was also updated for latest code improvements (Jenkins and Inman, 2004) and includes a listing of all model codes.



**Figure 4.** Closure depth contours (colors) as a function of grain size and significant breaker height for 12 s waves.

## RESULTS

During the present funding cycle (FY –04) the primary field validation efforts involved the MBP experiments at Martha’s Vineyard, MA. The Martha’s Vineyard experiment was conducted October 03-April 04 and was the first field validation test for VORTEX on a trailing edge coast. This site presented several new challenges for the model, including: 1) a very high energy winter wave environment, 2) heterogeneous bottom sediment stratigraphy consisting of layers of fine and coarse

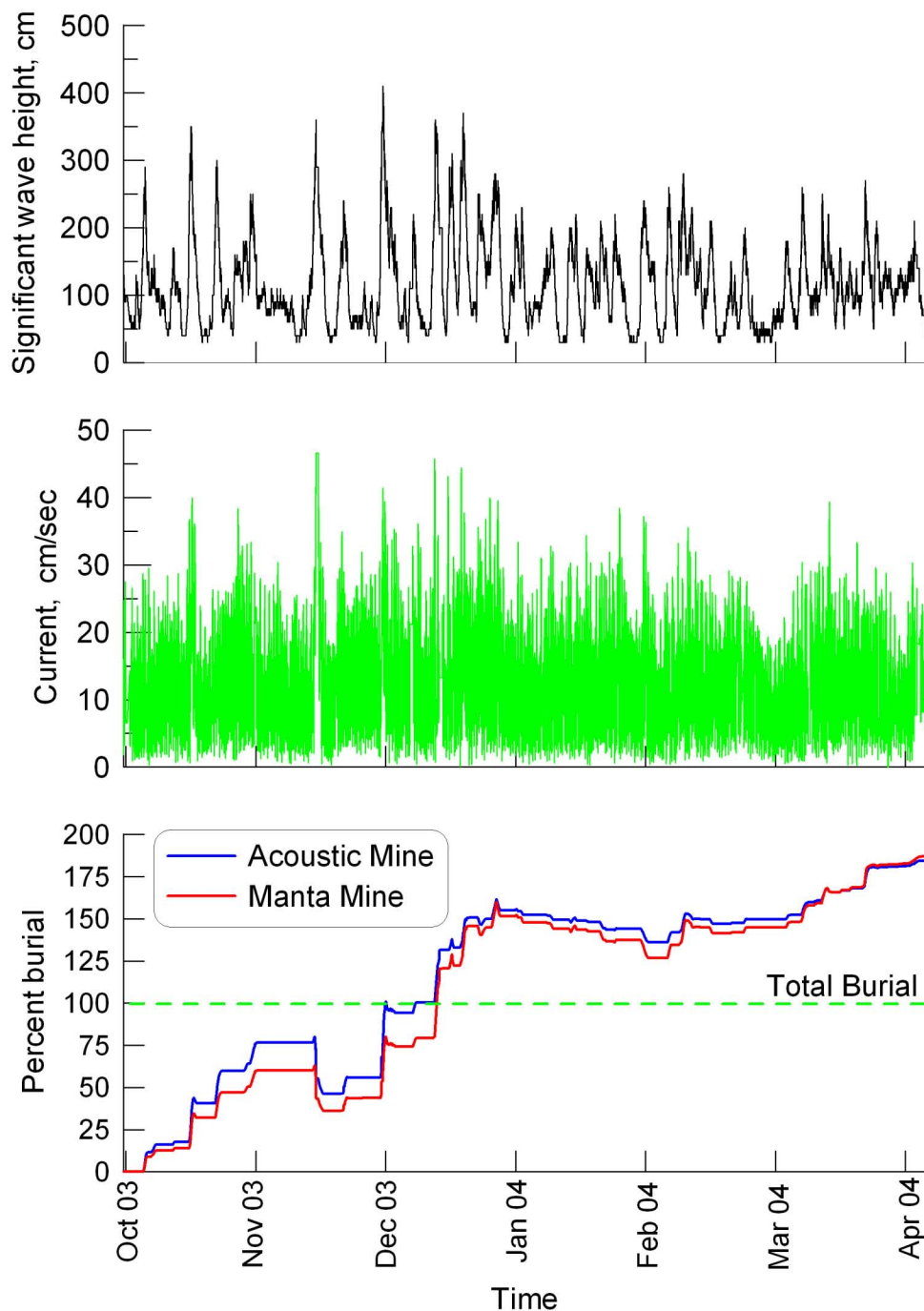
quartz sand segregated by scour ripple depressions, and 3) far field sources of fine-grained suspended sediment that episodically infiltrated the test site during calm periods between storm fronts. The source of the episodic suspensions of fines was believed to be the watersheds discharging into Buzzards Bay. The VORTEX model was initialized with high resolution bathymetry obtained from multi-beam sonar scans of the test site just prior to deployment of the mines. The model made predictions for two mine types, the AIM-2 acoustic mines (cylindrical) and the MANTA mine (truncated cone). The model was run in 72-hour forecast mode with 4-times weekly updates provided by FNMOC using the DIOPS wave/current forecast system. DIOPS uses the COAMPS weather model to drive the Wave Watch 3 wave generation model and the SWAN spectral model to propagate the forecasted waves into 22 meters of water depth at the perimeter of the test site. At that point the farfield forcing modules of VORTEX took over the wave shoaling computations and predicted the burial of the AIM-2 and MANTA mines planted at depths of 10m adjacent to the Martha's Vineyard Observatory.

Figure 5 (upper) indicates that extremely high-energy conditions prevailed at the Martha's Vineyard test site, particularly during the first half of the experiment (October 03- January 04). A total of 27 storms produced waves in 10 meter water depth with significant wave heights greater than 2 meters. Of those 27 storms, 7 produced waves in 10 meter water exceeding 3 meter significant wave heights. Superimposed on these storm waves were tidal currents averaging 25 cm/s with spring tide maximums exceeding 40 cm/s (Figure 5, middle). The combination of frequently occurring storm waves and moderately strong tidal currents resulted in predictions of rapid burial of both the quasi 2-dimensional AIM-2 mines and the 3-dimensional MANTA (Figure 5, lower). Burial was total by mid-December as confirmed by the acoustic sensors of the AIM-2. However the VORTEX model provides additional detail that is beyond both the self-registration capabilities of the AIM-2 mine, or the predictive capabilities of empirical or stochastic models.

- The farfield process architecture of VORTEX enables it to predict the depth of sediment overburden once burial is total. This is important information for predicting the adequacy of buried mine sensors such as buried object scanning sonar (BOSS), real time gradiometers (GRD) electromagnetic induction spectroscopy (EMIS using GEM-3) and marine mammal systems (Mk – VII). All these buried mine sensors have detection limits based on the depth of mine burial, and the capability of predicting the depth of burial once burial is complete is vital to determining the prudent use of these systems.
- VORTEX can predict exposure of already buried objects. (Note that the burial depth varies in Figure 5 after burial is total). VORTEX has successfully predicted seasonal exposure of buried MANTAS in 7 meters of water off Scripps Pier during 1997-2002.) The ability to predict subsequent exposure of buried mines is important not only to mine searching and minefield breaching but also to the management of the Navy's gunnery and bombing ranges (UXO sites).
- The nearfield process architecture of VORTEX, predicts the shape details of the partially buried mine silhouette and the surrounding bedform. Figure 6 shows a VORTEX model prediction of the bedform around a partially buried MANTA mine on 22 October 2003 during the Martha's Vineyard MBP experiment. Figure 7 shows the complementary prediction for AIM-2 acoustic mine and surrounding scour bedform on the same day. The scour bedforms are distinctly different for these two mine shapes and a portion of the scour hole on the down-wave side of each has in-filled with a layer of mud from the post-frontal settling of fine sediment. The acoustic reflection and scattering properties of

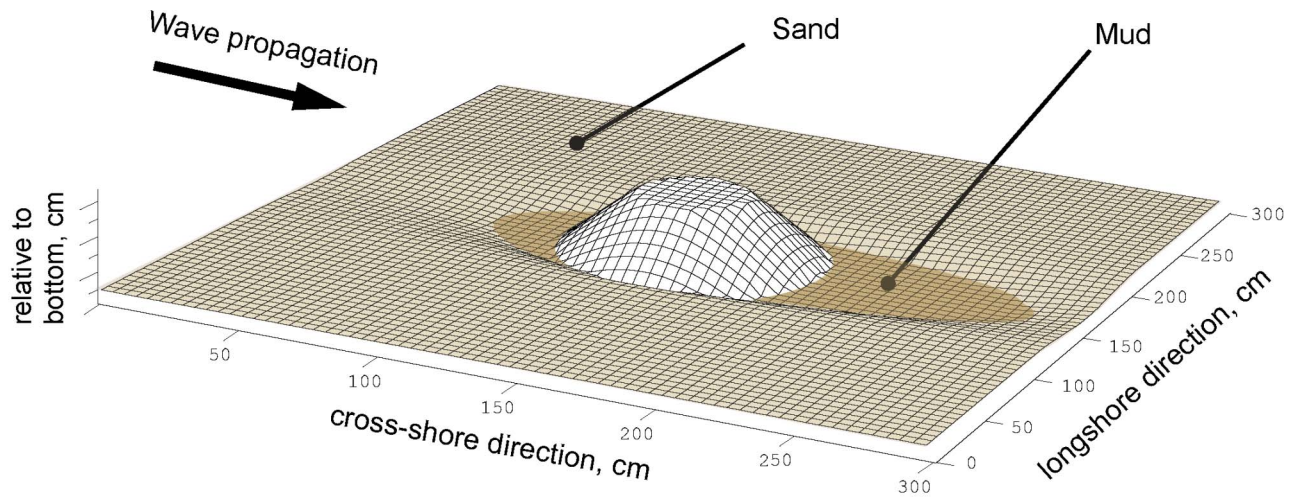


these distinctly different bedforms and sedimentary inhomogeneities would produce different detection cross-sections. Such information is vital to the feature recognition and classification libraries of the Computer Aided Detection/Computer Aided Classification (CAD/CAC) system. A VORTEX model prediction of the mine/bedform silhouette from could be used for *a priori* optimization of the tuning of mine search sonar to achieve maximum effectiveness.



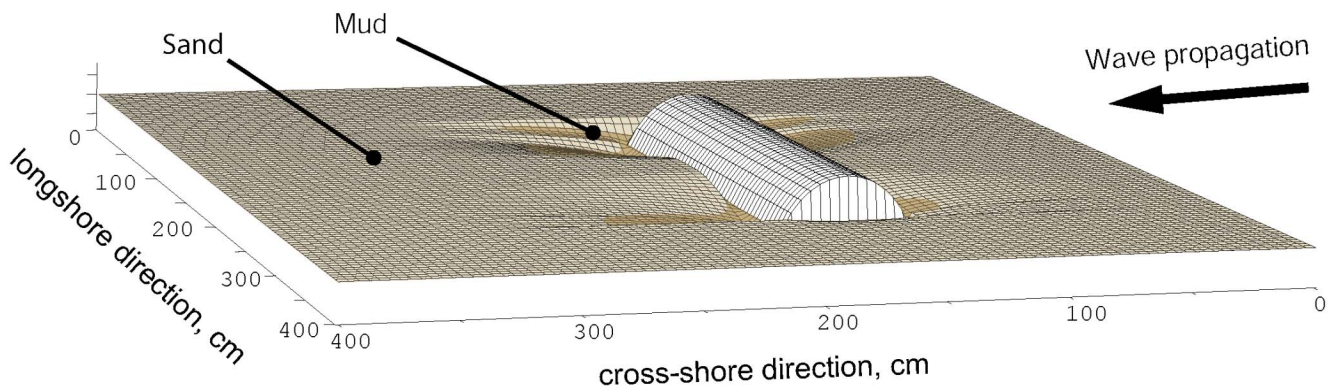
**Figure 5. Significant wave height (upper), current (middle), and predicted mine burial response (lower) at 10 m depth during the MBP experiments at Martha's Vineyard, MA, October 03 – April 04.**

Scour of Manta mine with fine sediment deposition  
in scour hole, 201 x 201 point computational mesh



**Figure 6. Simulated scour and bedform of Manta Mine,  
Martha's Vineyard Experiment, 22 Oct. 2003.**

Scour of Acoustic mine (AIM-2) with fine sediment deposition  
in scour hole, 201 x 201 point computational mesh



**Figure 7. Simulated scour and bedform of AIM-2 mine,  
Martha's Vineyard Experiment, 22 Oct. 2003.**

From the field validation trials and model sensitivity analyses we developed the following rules of thumb for mine burial (Inman and Jenkins, 2002):

- (1) Cylindrical mines will bury by a scour and roll sequence, during which the axis of the cylinder will align itself parallel to wave crests.
- (2) The cylindrical mine may move a number of mine diameters in the direction of wave propagation during the burial sequence.
- (3) Scour holes formed by cylindrical mines are deepest at the ends of the mine. During burial, cylindrical mines are buried more in the middle and become exposed at the ends.
- (4) Three-dimensional shapes (cones and hemispheres) bury more slowly than two-dimensional (cylindrical) shapes.
- (5) Small mines scour and bury deeper relative to their diameters than large mines, while absolute burial as measured from sediment surface to mine keel is greater for large mines.
- (6) Scour burial rates decrease as burial depth increases. This is because a partially buried mine presents a smaller silhouette to the flow.
- (7) Flat bottom mines (cones and hemispheres) will move less than one diameter during a burial sequence. However, hemi-oblate spheroids may flip over and move farther.
- (8) Burial rates due to scour by wave action are faster in the shallow water portion of the VSW zone.
- (9) Burial rates due to current action are usually faster in the offshore portion of the VSW zone (about 10-12 m depth) where coastal currents are more concentrated. However, longshore and rip currents may cause rapid burial and/or re-exposure in and near the surf zone (high tide to 3 m depth).
- (10) Impact burial is not a significant burial process in sandy environments (collision coasts, trailing edge coasts removed from river mouths, coral reef coasts). Impact burial is typically less than 10% in these environments.
- (11) Impact burial is the dominant burial process in muddy environments (deltaic marginal sea coasts and in estuaries and near river mouths of all coasts). Impact burial is typically 75% to more than 100% in these environments.

Burial rates of mines in the VSW zone will vary according to the characteristics that coastal type places on the hierarchy of interactive inputs. The input variables include the sediment grain size, roughness due to bedform, wave climate (energy flux and characteristic period), closure depth of seasonal profile changes, and littoral cell dimensions. In general, marginal sea environments have the slowest burial rates for local waves of moderate height (less than 1.5 meters) because the short fetches produce shorter, less intense waves. High-energy collision coasts have the highest burial rates following impact. This is due to the well-sorted fine sand typical for these coasts. Also, the narrow shelf and long wave periods of these high-energy coasts yield maximum onshore orbital velocities to induce scour. The burial rates along trailing edge coasts are similar to those on collision coasts, but the tendency for coarser sands along some of the former coasts lead to decreased rates.

## IMPACT/APPLICATIONS

The geomorphic coastal classification system provides a rational framework for organizing world coastal diversity into a manageable number of discrete categories. This can provide a powerful management and decision making tool for resource agencies as well as for the mine warfare community. With respect to the latter, the mix of tactics that the VSW detachment is likely to use in a mine threat environment is strongly effected by many of the morphology and seabed properties organized by this system. Therefore our coastal classification system is a logical adjunct to the Mine Warfare Environmental Decision Aids Library (MEDAL) and could be used to systematize the databases within MEDAL and the doctrine around it. The ability of the VORTEX model to resolve the mine/bedform silhouette make it a logical candidate for incorporation into CAD/CAC.

## TRANSITIONS

- a) Digital archiving of “Scour and Burial of Bottom Mines: A Primer for Fleet Use,”  
<http://repositories.cdlib.org/sio/reference/02-8>;
- b) Design of the seaframe for the VSW Mine Neutralization Marker, Type AFD.
- c) The submission of documented VORTEX code with user manual to the Ocean Atmosphere Model Library (OAML) is in progress.

## RELATED PROJECTS

The Vortex Model has been used as a design tool in the development of the VSW Neutralization Marker for the Marine Mammal Systems Branch, SPAWAR, Code D352. The model results for the VSW marker were used in the preparation of the Weapons System Explosive Safety Review Board (WSESRB) documents. Sensitivity analysis of the model is being applied to evaluations of new lane marking concepts by the VSW/MCM detachment at PMS-EOD 7023. VORTEX will also be used to diagnose unexploded ordnance sites (UXO) under a CNO sponsored program directed by the Naval Facilities Engineering Service Center, Code ESC 51, Ocean Engineering, Pt. Hueneme, CA.

The farfield modules of VORTEX form one member of a coupled model of coastal evolution now being developed under separate funding by our research group.

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